

Figure 1. Great Barasway F-66 geological background (Enachescu et al, 2010).

FWI implementation

Full Waveform Inversion (FWI) is a nonlinear problem that generates high-resolution velocity models by minimizing the misfit between observed and modeled shot data. The initial model is iteratively improved using a sequence of linearized inversions.

While conventional FWI relies on inverting for the refracted waves, the FWI method used in this example exploits the full wavefield. In deep-water environments, the refracted energy is limited due to a lack of long offsets, and most of the inversion is driven by the reflected energy. This allows us to update velocities much deeper in the subsurface.

Modeling is performed using the acoustic, two-way wave equation with pseudo-analytical extrapolation in time domain (Ramos-Martinez et al., 2011). The inversion uses a normalized form of the Born scattering kernel to compute the FWI gradient (Tarantola, 1984) through a variation of an Inverse Scattering Imaging Condition (ISIC). This gradient eliminates the migration isochrones that would generate high wavenumber artifacts which dominate conventional cross-correlation FWI gradient results (Ramos Martinez et al., 2016).

Additionally, we use a variable density model, necessary to model reflections in the absence of strong velocity contrasts. This results in better matching between modeled and recorded seismic events.

FWI uses minimally processed shot gathers and can be run early in an imaging project. Therefore a high-resolution velocity model can be created in parallel with the time pre-processed data, minimizing the impact of model building on project turnaround (Figure 2).

FWI velocity model building workflow and results

FWI relies on three key components: a wavelet, input data and an initial velocity model. The wavelet was extracted from the raw data.

The input data, was prepared as follows:

- 1) Noise is removed from the raw shot data
- 2) Phase analysis is performed on the denoised data in octave panels. This indicated that the FWI could be started in the 2 Hz to 4 Hz bandwidth.
- 3) A second pass of noise attenuation is run targeting these low frequencies.

To maintain phase consistency with the FWI wavelet we also convert the data to minimum phase. Starting inversions with the lowest possible frequency contained in the GeoStreamer data and an updated velocity model reduces the risk of cycle-skipping.

For this purpose, we created a VTI depth velocity model from the raw data by running several wavelet shift tomography updates (Sherwood et al., 2008 and Sherwood et al., 2011). Initial anisotropic parameters were extracted from well information and later updated through tomographic inversion.

We recursively inverted using increasing bandwidths from 4 Hz to 25 Hz (Figure 2). For each bandwidth, the velocity model was updated so that the misfit between recorded and modeled shots was reduced. The process was then iterated until the FWI cost function flattens. The quality control metrics of convergence were based on both amplitude misfits and cross-correlation between modeled and field data.

After each frequency bandwidth inversion, additional quality control was performed in both data and image domains to ensure that model resolution and migrated image are improved. Such QCs included modeled shots and receiver gathers compared to recorded data, FWI velocity perturbation, migrated gathers and stacks before and after the FWI inversion.

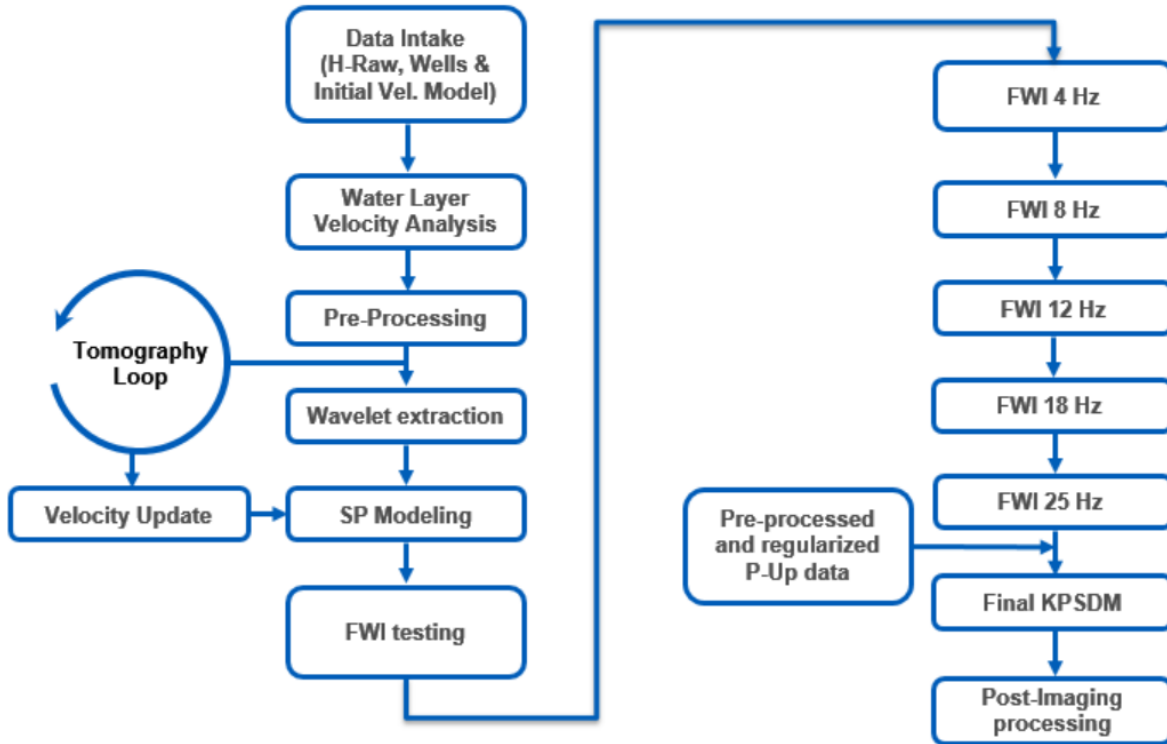


Figure 2. FWI velocity model building workflow.

The resulting FWI velocity model had fine resolution capturing the small-scale geological features in the deeper, Tertiary section (Figure 3). Using reflection energy, several velocity inversions were modeled, particularly in the shallow overburden. We also observed that our updated velocity model closely follows the regional structural trend in the deeper Jurassic section, despite the limitations of the offset coverage and illumination.

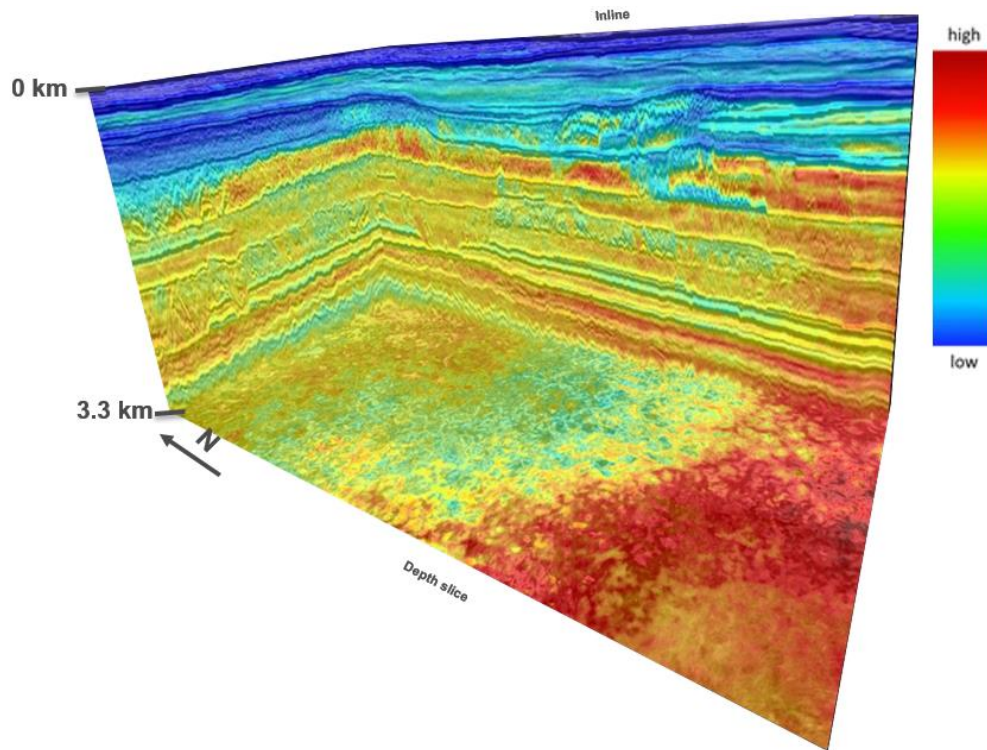


Figure 3. 3D view of the velocity model in the Tertiary/Cretaceous section after the 25Hz FWI update.

The high-resolution FWI velocity model was used in Kirchhoff Prestack Depth Migration and Wave-Equation LSM (Alcantara et al, 2020), leading to better-defined structures and faults in the deeper sections, which mitigate potential drilling risks.

Lastly, the FWI model was used in quantitative interpretation for the Low Frequency Model (LFM) in elastic property generation (Martin and Reiser, 2019). It enabled an accurate match between absolute acoustic inversion and the Great Barasway well log.

Conclusions

A unique implementation of FWI was successfully used on deep-water, dual-sensor seismic data from the Orphan basin, inverting for both reflected and refracted wavefields. The results capture high-velocity contrasts and velocity inversions in the geologically complex overburden that were missing from the initial model.

The ultra-low frequency dual-sensor data set enabled FWI to start from the 2-4 Hz frequency band, reducing the risk of cycle-skipping, and allowed the velocity model building to start in parallel with the pre-imaging phase of the project. The model was then used to provide high-end depth imaging, including Kirchhoff and Wave-Equation Least-Squares migrations. Finally, our model was used in elastic property generation, all of which reduced uncertainty.

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References

Alcantara, T., Frugier, E., Virlovet, B., Montevecchi, N., Cameron, D., Wright, R., 2020. Image enhancement through data domain least squares migration: an Orphan basin example. Abstract under review. GeoConvention, May 2020.

Enachescu, M., Atkinson, I., Hogg, J., McCallum, D., Rowe, C., 2010. Kimmeridgian Source Rock SuperHighway in the North Atlantic. Abstract. AAPG Annual Convention and Exhibition, April 2010.

http://www.searchanddiscovery.com/pdfz/abstracts/pdf/2010/annual/abstracts/ndx_enachescu.pdf.html

Lu, S., X., Li, A. A., Valenciano, N., Chemingui, and C., Cheng, 2017, Least-Squares Wave-Equation Migration for Broadband Imaging: 79th Annual International Conference and Exhibition, EAGE, Extended Abstracts, doi:

<https://doi.org/10.3997/2214-4609.201700803>

Martin, T., Reiser, C., 2019, Integrating FWI Models and Broadband Data for Elastic Property Generation, What is Appropriate?. Second EAGE/PESGB Workshop on Velocities, EAGE/PESGB, Extended abstracts, doi:

<https://doi.org/10.3997/2214-4609.201900043>

Ramos-Martinez, J., S., Crawley, Z., Zou, A.A., Valenciano, L., Qui, and N., Chemingui, 2016, A robust gradient for long wavelength FWI updates: 78th Annual International Conference and Exhibition, EAGE, Extended Abstracts, SRS2, doi: <https://doi.org/10.3997/2214-4609.201601536>

Sherwood, J., Sherwood, K., Tieman, H. and Schleicher, K. [2008] 3D beam pre-stack depth migration with examples from around the world. 78th SEG Annual Meeting, Expanded Abstracts, 438–442.

Sherwood, J., Jiao, J., Tieman, H., Sherwood, K., Zhou, C., Lin, S. and Brandsberg-Dahl, S. [2011] Hybrid tomography based on beam migration. 81st SEG Annual Meeting, Expanded Abstracts, 3979–3983.

Tarantola, A., [1984] Inversion of seismic reflection data in the acoustic approximation, *Geophysics*, 49, 1259-1266.